Main Injector Corrector Strength Analysis

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1 Introduction

The tracking program, Tevlat, is used to estimate dipole corrector strengths for the Main Injector. The particular issue addressed is whether the present Main Ring correction dipoles and their power supplies are adequate for high field orbit correction in the Main Injector. Tevlat was chosen because the real Main Injector lattice exists in the appropriate input format, and the errors leading to orbit distortions can be easily included as zeroeth order multipole moments in the multipole file. These can be generated with gaussian distributions. Additionally, orbit correction can be analyzed in the presence of the large saturation sextupole at 150 GeV/c.

2 Correction Elements

The strengths of the Main Ring correction elements are shown below.

Table 1: Dipole Corrector Strengths

Dipole Type	Strength in G-m/a	Bend Angle at 150 GeV/c in mrad per amp
Normal Horizontal	34.5	.007
Normal Hor with spacer	25.9	.0053
Vertical	20.2	.004

The spacer is required if existing horizontal dipoles are used bacause the normal 1.5 inch vertical gap of the correction dipoles is not large enough for the 2 inch MI beam pipe. I include the table entry for the dipole without spacers so that calculations can be made for different width spacers.

The present power supplies are capable of 12 amps peak and 7 amps rms.

3 Closed Orbit Errors

The sources of closed orbit errors are the dipoles and the quadrupoles. The dipoles can generate closed orbit errors either by field errors or roll errors. I assume that roll errors produce purely vertical deflection. The program that I use to set up the multipole file expects the input to be in units at 1 inch. For dipole errors the input needs to be units, and thus 10^{-4} of the lattice dipole field. For roll errors, the vertical kick will be $\theta sin\alpha$ where θ is the bend angle of the dipole and α is the roll angle. The small angle approximation applies so that the vertical kick is $\theta\alpha$. Thus roll angles, taken in tenths of milliradians, are equivalent to units of skew dipole.

The dipole kick given by a misaligned quadrupole is x/f where x is the alignment error and f is the focal length of the quadrupole. This can be expressed as:

$$\phi = \frac{x}{f} = x\left(\frac{B'l}{B\rho}\right) = \left(\frac{B'}{B\rho}\right)xl$$

The dipole multipole content of a quadrupole is not well defined, but I have allowed it to be defined as x in the above equation (assuming that the x is taken in $meters^{-4}$ or tenths of mm. In other words if a quadrupole is defined as being misaligned with an error of $.2mm$, then entering 2 units will produce the proper kick angle. This paramaterization correctly handles quadrupoles of differing length.

Table 2 lists the assumptions made regarding errors, and the entries used by the program mi_fields in generating the multipole file.

Table 2: Sources and Magnitudes of Dipole Errors

Error Type	Error Plane	Sigma of Distribution	Units
Dipole Field Error	Horizontal	5×10^{-4}	5.0
Dipole Roll Error	Vertical	.25 mrad	2.5
Quad misalignment	Horizontal	.25 mm	2.5
Quad misalignment	Vertical	.2 mm	2.0

Note again that because of the use of the tracking environment to do this simulation, and the need to use units as input, a sense of perspective can be lost. One unit of dipole in a dipole is a kick of 2.1 $\mu\,radians$, whereas one unit of dipole in a quadrupole is a kick of 8.4 $\mu\,radians$. These numbers are specific to the MI lattice.

BPM Errors

The Tevlat program does not allow for BPM errors. I did not take the time to include them in the code, and I would like to argue that they are not needed in the simulation. All orbit corrections are made relative to a set of closed orbit measurements made in the past. Based on my experience with the Main Ring and the Tevatron, we will not do substantial aperture scans at high field. There will be several places in the ring which require precise positioning, but these positions will be defined by experiment and the resulting position will become the "desired position" for future orbit corrections. BPM errors, whether due to misalignment or electronic sources should be less than 1 mm, and therefore represent a small fraction of the of the precorrection error (which as will be discussed is on the order of $\pm 8mm$.) My own opinion is that at 150 GeV/c we will not need to correct to better than a millimeter, and that omitting BPM errors will not lead to a result which underestimates corrector strength.

4 Software

Several different programs have been used in this analysis.

mi_fields - This program has always been a part of my tracking package. It reads the lattice information, and when provided with various data statements and other sources of information, it fills the multipole array. It was modified for this application to read a file of correction element strengths and insert them into the multipole array at the corrector locations.

tevlat - It simulates the accelerator. Provided with the lattice and a set of multipole errors, it produces a file containing the closed orbit.

orbit_statistics - This program reads the file produced by tevlat and lists the rms errors. The output is shown below:

```
NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors
The Horizontal average is    -0.131 and rms    4.35822
The Vertical   average is    -0.118 and rms    1.51116

The statistics at Vertical Detectors
The Horizontal average is    -0.153 and rms    2.22157
The Vertical   average is     0.013 and rms    3.30783

The statistics at All Detectors
The Horizontal average is    -0.142 and rms    3.41452
The Vertical   average is    -0.050 and rms    2.59353
```

Thus the rms error for each type of detector is independently calculated along with the rms for all detectors. This addresses the issue of whether detectors are needed at every quadrupole, or only those that focus in the plane of detection.

orbit_corr - This program uses a three bump algorithm to calculate dipole corrector strengths. It assumes one detector per corrector. It produces a file (called mice for main injector correction elements) which is then used by mi_fields to produce a multipole array that includes corrections as well as errors.

All of the programs mentioned are in

/home/quad/rod/tevlat/mi

5 Results

Analysis was done with several different seeds. A more extensive analysis was done with a partiular seed (33333). In this case I include results for a variety of different nonlinear cases. In each case the orbit was corrected using the linear lattice functions, but the simulation was modified to include the following:

- no nonlinearities, this is the linear lattice, no multipoles were included in dipoles or correctors while running tevlat
- sextupoles to correct natural chromaticity to zero in both planes were turned on
- 150 GeV/c saturation multipoles were added and sextupoles were tuned to correct chromaticity to zero in both planes
- 150 GeV/c saturation multipoles were maintined and sextupoles were tuned to make chromaticity of +20 in both planes

The saturation multipoles were included with no random component.

Figures and tables associated with the seed 33333 are prefixed with the letter A. Table A-1 is the orbit statistics for the purely linear case. The top half is the data prior to correction and the bottom half is after correction. Table A-2 is for the case with natural chromaticity correction only. The others follow and are labeled. Figures A-5 and A-6 are plots of the dipole strengths used in the correction The largest vertical corrections are about $60\,\mu\,radians$ and the largest horizontal corrections are about $80\,\mu\,radians$. (These bend angles exceed the capabilities of the correctors as specified in Table 1. See "Conclusions" for a discussion of these limitations.)

Table B-1 contains data for a second seed, 23847. In this and all further datasets, only data for the worst case (all saturation multipoles and chromaticities corrected to +20) are considered. Figures B-2, B-3 and B-4 show the orbit before and after correction and the corrector strengths needed for correction. In this case the maximum corrector strengths are $62\,\mu\,radians$ for the horizontal plane and $42\,\mu\,radians$ for the vertical plane. Further figures are not presented, but the data for all seeds are shown in Table 3. For each seed, the data shown are for the case with all saturation multipoles on, and chromaticity correction to +20.

Table 3: Summary of Data

Seed	H rms after corr. (mm)	V rms after corr. (mm)	H Corr. rms (μrad)	V Corr. rms (μrad)	H Corr. Max (μrad)	V Corr. Max (μrad)
33333	.19	.13	29	22	82	57
23847	.10	.07	28	17	62	42
30298	.25	.07	34	22	85	61

6 Conclusions

Based on this analysis it appears that the use of the present correction elements and the new Main Ring Correction Element power supplies is adaquate for high field correction in the Main Injector. This statement assumes the following:

- The power supplies really can make it to 12 amps, as advertised.
- High field correction is not needed to better than a few millimeters except at particular locations in the ring where special magnets and or power supplies could be used. In other words we should be able to get away with partial correction elsewhere.
- Some quad alignment can be done to help in locations where extreme corrector strength is needed.
- A more sophisticated correction algorithm might be used which would lead to a reduction in the peaks of corrector strengths. This is particulary true around the long straight sections where the limited phase advance contributes to the need for stronger kicks from the correctors.

The three bump correction scheme works in the presense of nonlinearities as expected. My opinion in regard to the number of detectors is that this analysis indicates no need for detectors at the quadrupoles which focus in the opposite plane.

Statistics before correction

```
NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors
The Horizontal average is      0.040 and rms    5.81636
The Vertical   average is      0.129 and rms    3.23601

The statistics at Vertical Detectors
The Horizontal average is      0.162 and rms    3.01993
The Vertical   average is     -0.044 and rms    6.56839

The statistics at All Detectors
The Horizontal average is      0.103 and rms    4.57587
The Vertical   average is      0.040 and rms    5.21705
```

Statistics after Correction

```
NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors
The Horizontal average is      0.000 and rms    0.00714
The Vertical   average is     -0.006 and rms    0.09526

The statistics at Vertical Detectors
The Horizontal average is     -0.009 and rms    0.11055
The Vertical   average is      0.000 and rms    0.00769

The statistics at All Detectors
The Horizontal average is     -0.005 and rms    0.07955
The Vertical   average is     -0.003 and rms    0.06632
```

Seed 33333

no sextupoles, not even chromaticity correcting sextupoles for natural chromaticity

Table A-1

```
The analysis is for seed 33333, and chromaticity correctors
turned on to correct natural chromaticity.  No high order
multipoles in dipoles


NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors
The Horizontal average is     -0.015 and rms    5.85313
The Vertical   average is      0.135 and rms    3.26138

The statistics at Vertical Detectors
The Horizontal average is      0.139 and rms    3.03819
The Vertical   average is     -0.044 and rms    6.62266

The statistics at All Detectors
The Horizontal average is      0.065 and rms    4.60475
The Vertical   average is      0.043 and rms    5.25978


NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors
The Horizontal average is      0.054 and rms    0.10162
The Vertical   average is     -0.010 and rms    0.12041

The statistics at Vertical Detectors
The Horizontal average is      0.023 and rms    0.12885
The Vertical   average is      0.000 and rms    0.11861

The statistics at All Detectors
The Horizontal average is      0.038 and rms    0.11721
The Vertical   average is     -0.005 and rms    0.11923
```

Table A-2

:ed 33333

150 GeV/c saturation multipoles in the dipoles

```
-8.3 units sextupole   \
-1.25 units decapole   |  no randoms
-.2 units 14-pole      /
```

chromaticity corrected to 0,0

NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors

The Horizontal	average is	0.003	and rms 5.68575
The Vertical	average is	0.129	and rms 3.14460

The statistics at Vertical Detectors

The Horizontal	average is	0.123	and rms 2.95322
The Vertical	average is	-0.037	and rms 6.38358

The statistics at All Detectors

The Horizontal	average is	0.065	and rms 4.47350
The Vertical	average is	0.043	and rms 5.07013

NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors

The Horizontal	average is	0.036	and rms 0.21778
The Vertical	average is	-0.004	and rms 0.11279

The statistics at Vertical Detectors

The Horizontal	average is	0.033	and rms 0.16547
The Vertical	average is	-0.007	and rms 0.20769

The statistics at All Detectors

The Horizontal	average is	0.034	and rms 0.19198
The Vertical	average is	-0.006	and rms 0.16819

Table A-3

ᴝed 33333

150 GeV/c saturation multipoles in the dipoles

```
-8.3 units sextupole  \
-1.25 units decapole  |  no randoms
-.2 units 14-pole     /
```

chromaticity corrected to 20,20

NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors
The Horizontal average is   -0.034 and rms   5.70583
The Vertical   average is   0.133 and rms   3.16303

The statistics at Vertical Detectors
The Horizontal average is   0.107 and rms   2.96340
The Vertical   average is   -0.037 and rms   6.42256

The statistics at All Detectors
The Horizontal average is   0.039 and rms   4.48936
The Vertical   average is   0.045 and rms   5.10088

before correction

after correction

NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors
The Horizontal average is   0.074 and rms   0.22106
The Vertical   average is   -0.007 and rms   0.10283

The statistics at Vertical Detectors
The Horizontal average is   0.055 and rms   0.17153
The Vertical   average is   -0.007 and rms   0.15933

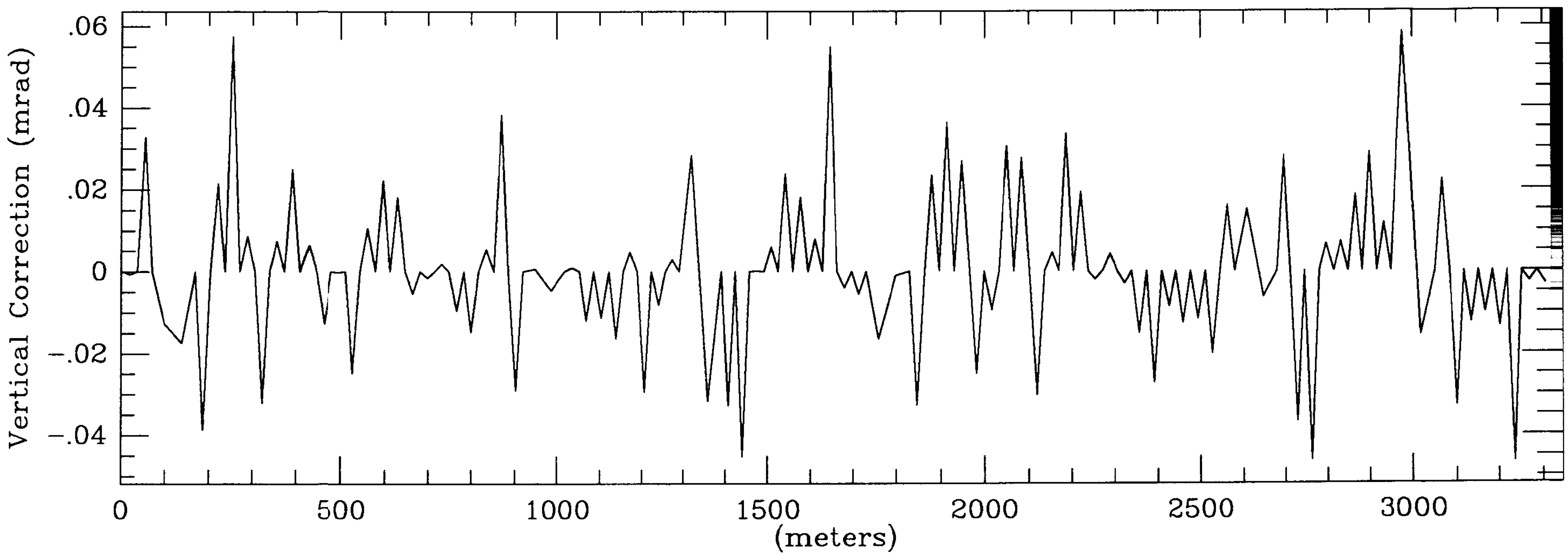
The statistics at All Detectors
The Horizontal average is   0.064 and rms   0.19669
The Vertical   average is   -0.007 and rms   0.13465

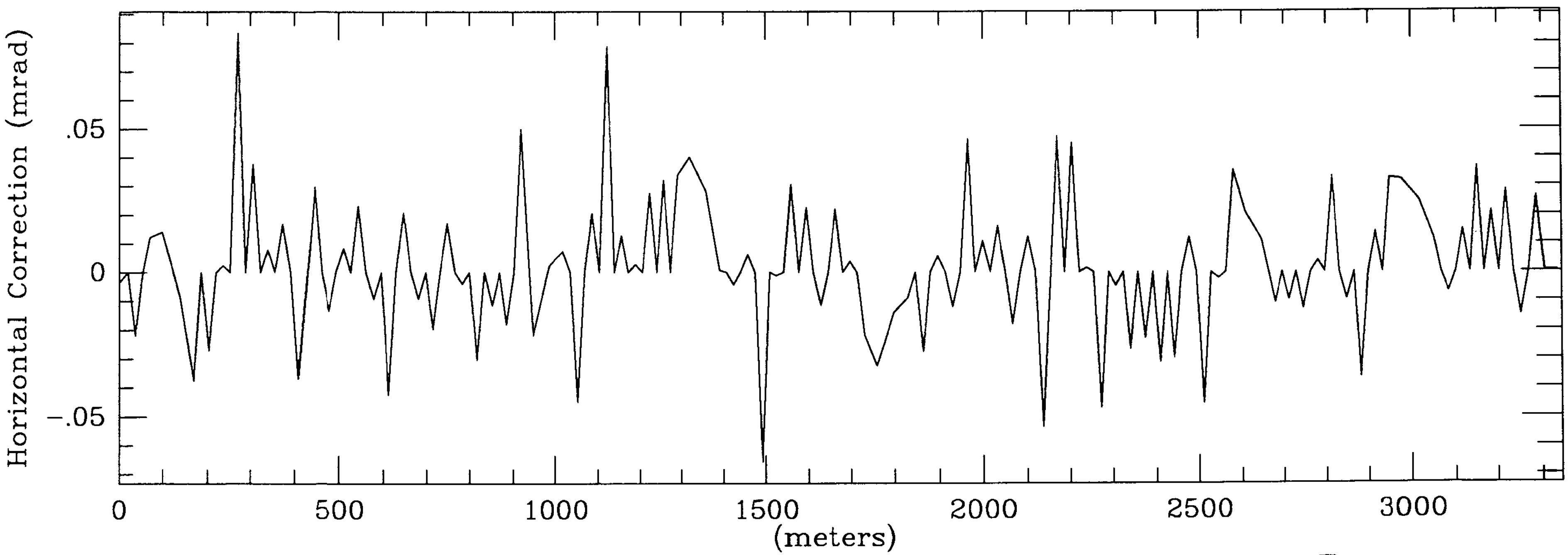
mice statistics in microradians

The Horizontal average is   2.164 and rms   29.35613
The Vertical   average is   -0.364 and rms   22.34131

The largest Hor is   82.200 and the largest Ver is   57.000

Table A-4

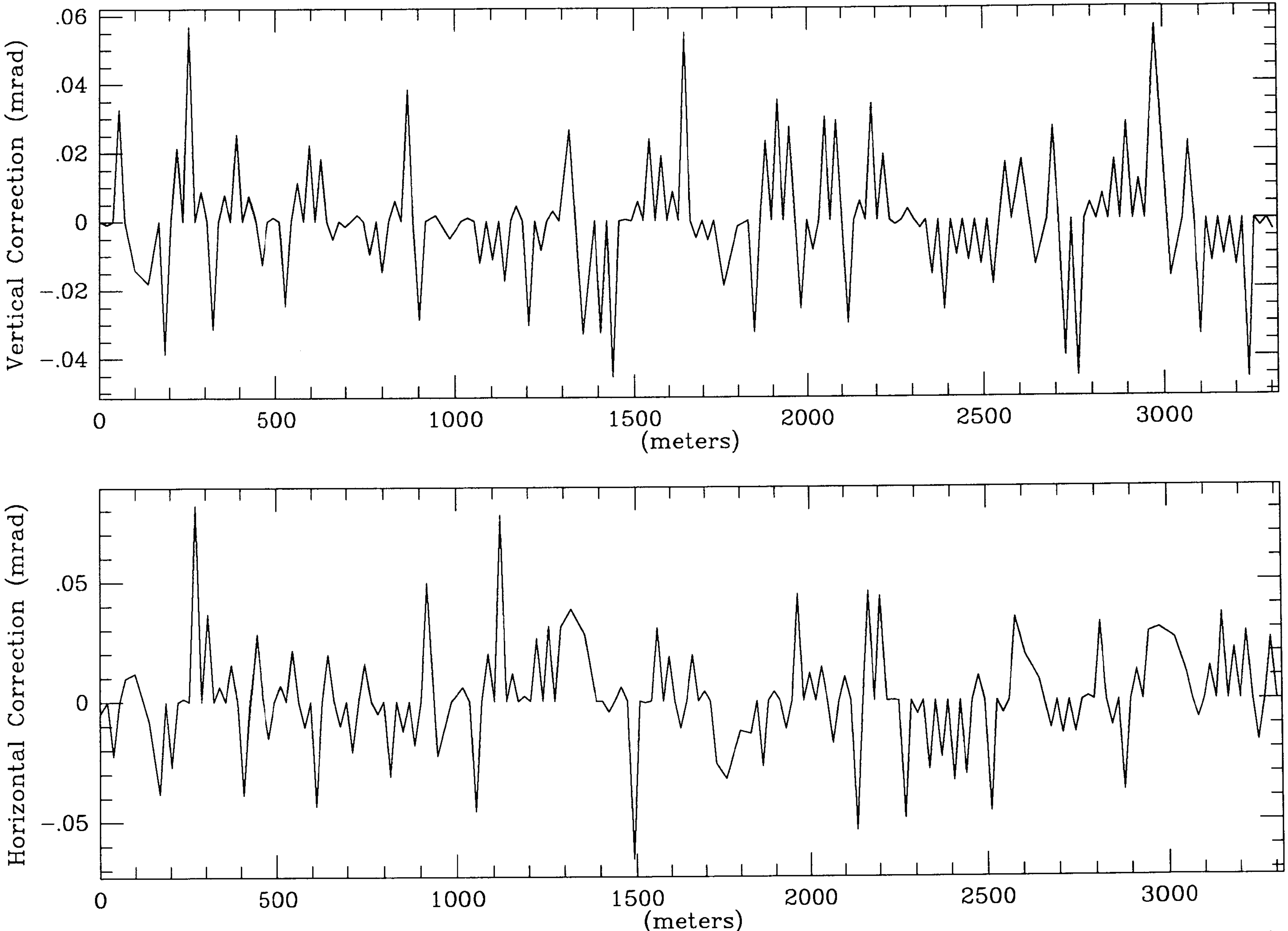




Seed 33333

Figure A-5

(ection for: Natural chromaticity compensation



Seed 33333

saturation multipoles in dipoles
chromaticity correction to +20, +20

Figure A-6

ɘed 23847

150 GeV/c saturation multipoles in the dipoles

```
-8.3 units sextupole  \
-1.25 units decapole  |  no randoms
-.2 units 14-pole     /
```

chromaticity corrected to 20,20

NUMBER OF INPUT RECORDS =   178

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors

The Horizontal	average is	-0.033	and rms	4.80329
The Vertical	average is	0.114	and rms	1.51073

The statistics at Vertical Detectors

The Horizontal	average is	-0.053	and rms	2.57375
The Vertical	average is	0.057	and rms	3.33873

The statistics at All Detectors

before correction

The Horizontal	average is	-0.043	and rms	3.80596
The Vertical	average is	0.084	and rms	2.61302

NUMBER OF INPUT RECORDS =   178

after correction

There are   86 Horizontal Detectors
There are   92 Vertical Detectors

The statistics at Horizontal Detectors

The Horizontal	average is	0.030	and rms	0.08721
The Vertical	average is	0.007	and rms	0.07233

The statistics at Vertical Detectors

The Horizontal	average is	0.031	and rms	0.12140
The Vertical	average is	-0.001	and rms	0.07539

The statistics at All Detectors

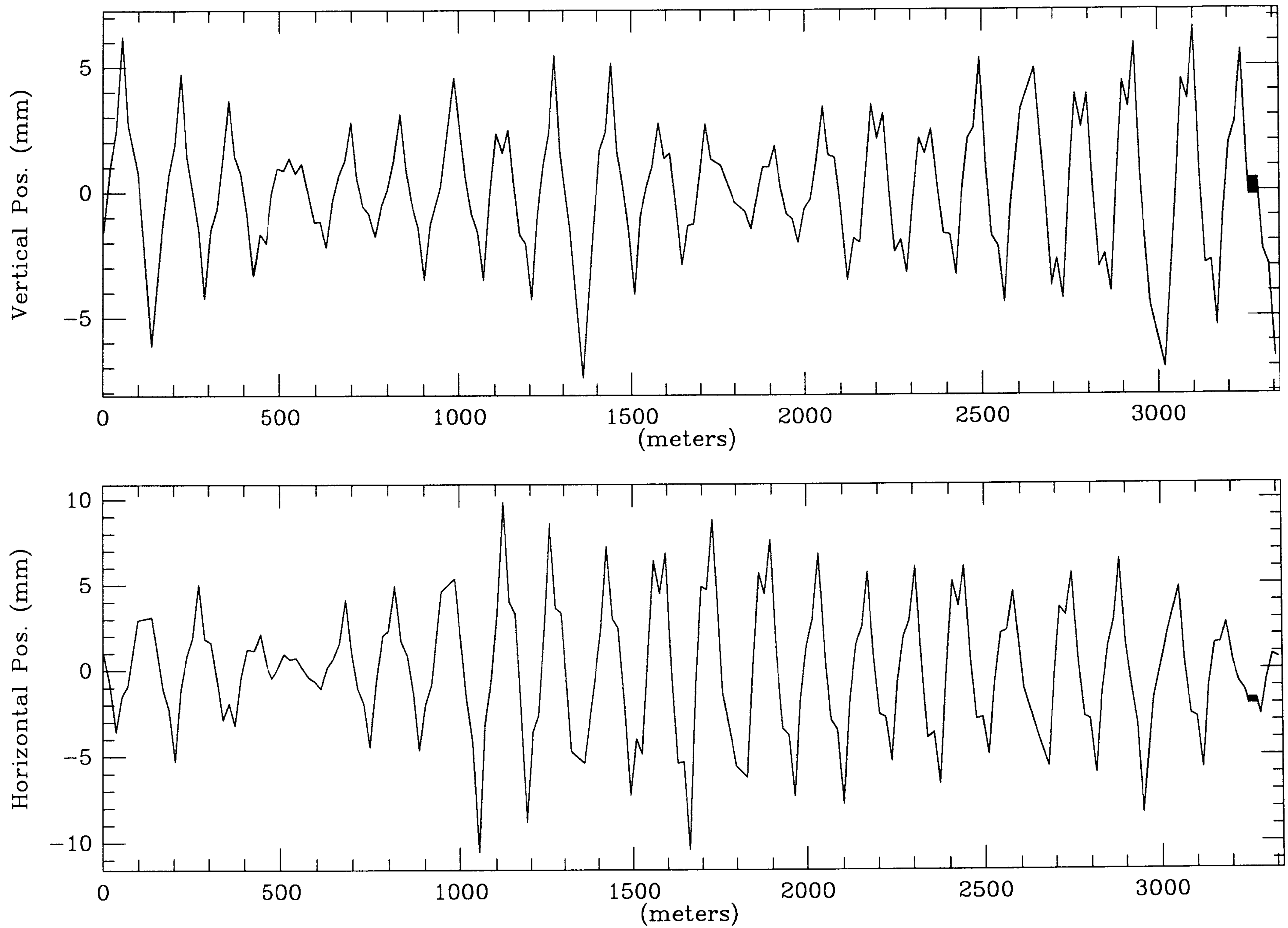
The Horizontal	average is	0.031	and rms	0.10597
The Vertical	average is	0.003	and rms	0.07382

mice statistics in microradians

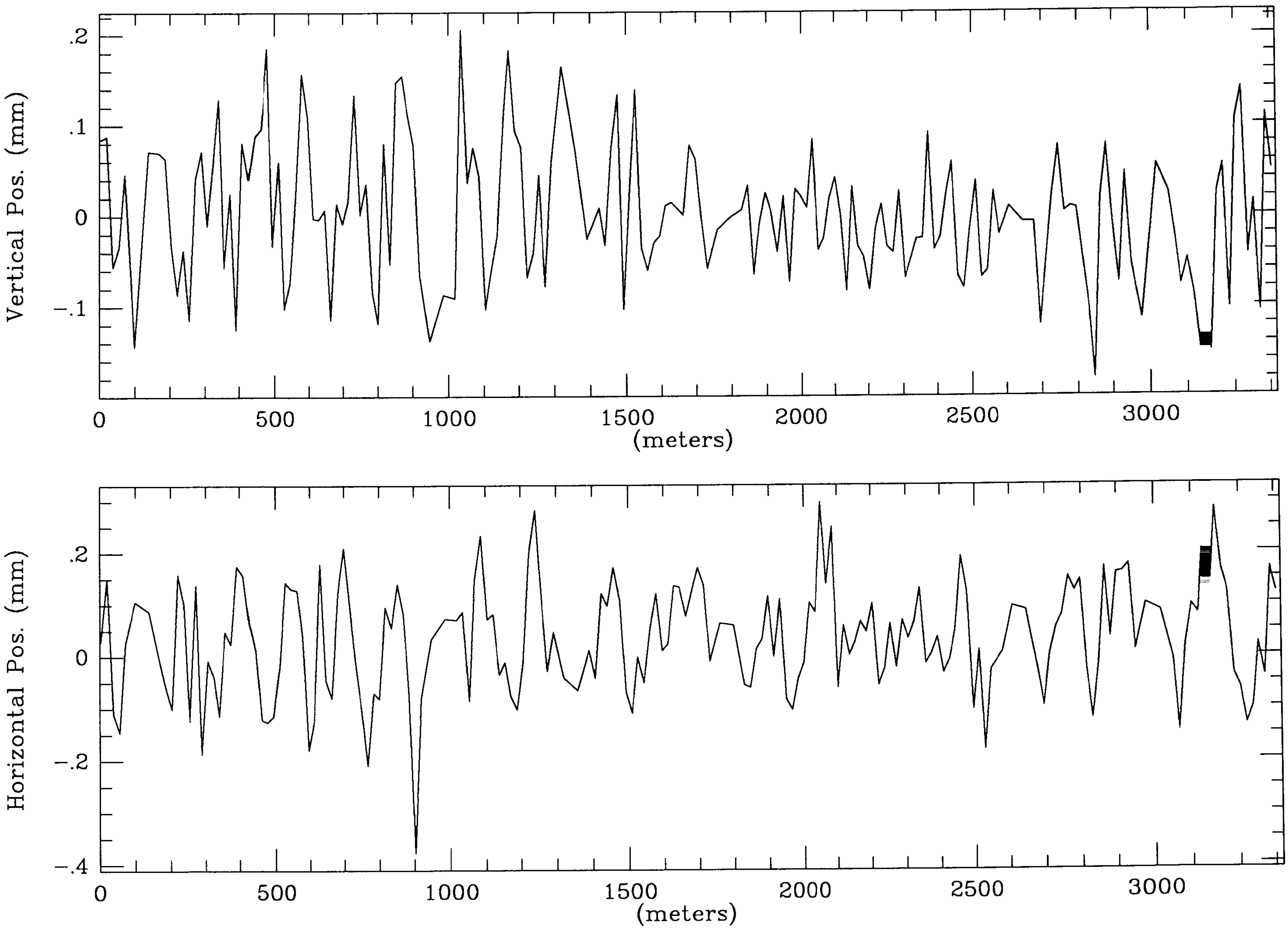
The Horizontal	average is	-3.320	and rms	28.08451
The Vertical	average is	-2.344	and rms	16.59531

The largest Hor is   62.300 and the largest Ver is   41.500

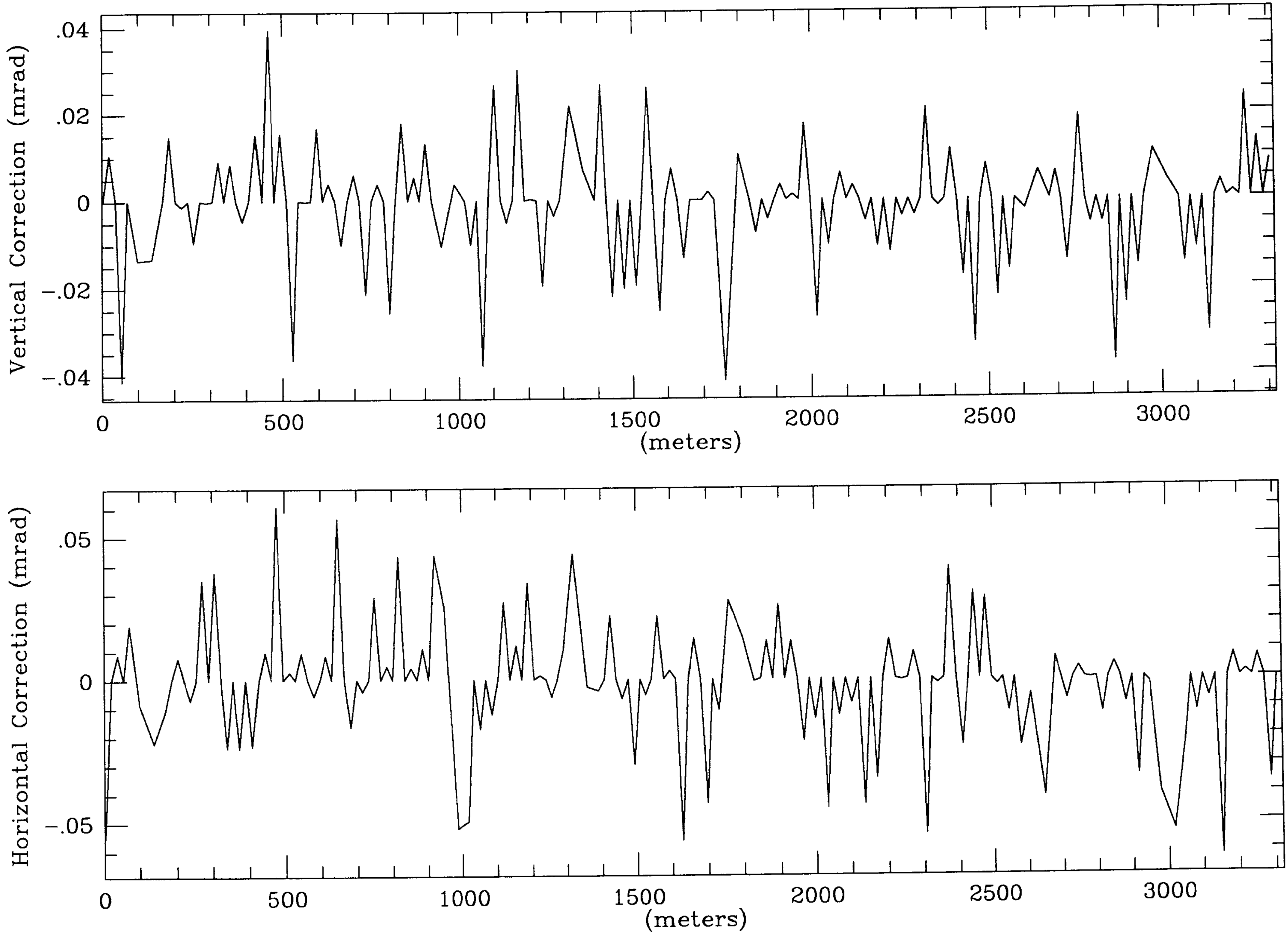
Table B-1



Seed 23847 Figure B-2 before correction



Seed 23847 Figure B-3 After correction



Seed 23847

Figure B-4